

## The Atmospheric Hydrologic Cycle over the Southern Ocean and Antarctica from Operational Numerical Analyses\*

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### ABSTRACT

Moisture budget calculations for Antarctica and the Southern Ocean (40°–72°S) are performed using operational numerical analyses from the European Centre for Medium-Range Weather Forecasts (ECMWF), the National Meteorological Center (NMC), and the Australian Bureau of Meteorology (ABM). The analyses are intercompared for an 8-yr period from 1985 to 1992 and are evaluated against representative rawinsonde sites, which are considered accurate depictions of moisture transport at these sites.

The comparisons to East Antarctic rawinsondes and those from Macquarie Island show the ECMWF analyses to be superior in reproducing sounding values at each level. While results are highly variable depending on the station location, agreement of the ECMWF analyses to zonally averaged sounding moisture flux values along the East Antarctic coast is very close. The zonally averaged annual meridional moisture flux, for example, is within as little as 0.03 g kg<sup>-1</sup> m s<sup>-1</sup>, or 2% at the surface. This is particularly good considering the highly variable inflow and outflow patterns along the Antarctic perimeter. The NMC and ABM analyses generally underestimate transport at each level; error cancellation occurs during vertical integration however. A comparison of moisture convergence for East Antarctica with values calculated from rawinsonde data indicates the ECMWF analysis is within 5 mm yr<sup>-1</sup> of the observed value, while the NMC result is severely deficient. Overall these results are not surprising given the coarse resolution and spectral nature of the analyses. The ability of the ECMWF analyses to reproduce the observed moisture transport at each level is reassuring.

Comparison of the moisture transport convergence derived from the numerical analyses with previous moisture flux studies over the Southern Ocean reveals general agreement in the location of the boundary between the moisture source and sink. The ECMWF and NMC analyses place the convergence maximum slightly farther south than has been previously found. It is inferred that this results from the blocking effect of the Antarctic coastal topography. At full resolution this point is at approximately 64°S.

Long-term net precipitation (precipitation minus sublimation/evaporation) derived from the numerical analyses is somewhat smaller than values determined by glaciological methods. Net precipitation varies interannually by 25%, with most of the variation concentrated in the South Pacific sector, the region of greatest poleward moisture transport.

The results presented here offer a substantially more positive outlook on the prospects of determining continental-scale precipitation trends in Antarctica through atmospheric methods than has been previously found and demonstrate that the ECMWF analyses provide generally good estimates.

### 1. Introduction

The Antarctic ice sheets constitute one of the largest reservoirs of fresh water available on earth. The mass

balance of the ice sheets in Antarctica potentially could have a major impact on global sea level variations (e.g., Jacobs 1992). If forecasts of the global warming phenomenon are realized, the amount of water stored on land in Antarctica will be significantly affected (Oerlemans 1982, 1989; Jacobs 1992). A major component of the Antarctic ice sheet mass balance is the areally averaged accumulation rate (precipitation minus losses due to sublimation/evaporation, drift snow transport divergence, and runoff); its variability, however, is largely unknown. Measuring precipitation over Antarctica is a complicated matter. Along the coast, the effect of wind on gauge collections is large, and contamination frequently results from blowing snow. In the in-

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terior, precipitation rates are usually less than the minimum snow gauge resolution. Although glaciological methods are accurate (Lorius 1983), the limited spatial coverage and the potentially high spatial variability of accumulation rates make annual precipitation estimations difficult and presently limit this approach to yielding a multiannual depiction. These conditions render direct measurement techniques impractical (Bromwich 1988).

In this study, the feasibility of computing net precipitation (precipitation minus sublimation/evaporation) for Antarctica and the surrounding sea-ice zone from operational numerical analyses via the moisture budget approach is examined. The analyses are evaluated for the years 1985–92 and are from the European Centre for Medium-Range Weather Forecasts (ECMWF) TOGA (Tropical Oceans Global Atmosphere) Program Archive II, the U.S. National Meteorological Center (NMC), and the Australian Bureau of Meteorology (ABM). The numerical analyses are a unique and valuable tool for atmospheric study, representing the most comprehensive assimilation of meteorological data available. Although exhaustive studies of objective numerical analyses have been completed from a global perspective (Trenberth and Olson 1988a,b,c; Trenberth 1992), the skill of these analyses in high southern latitudes is not well known. A few studies have been conducted using this approach for shorter time periods. Yamazaki (1992) employed the NMC analyses in a study similar to the one presented here for the years 1986–90 and is perhaps the most comprehensive study to date of Antarctic precipitation as determined from numerical analyses using the moisture budget approach. The estimated annual accumulation over Antarctica was found to be  $135 \pm 18$  mm. Precipitation values were generally larger during the winter months. A weak semiannual oscillation with peaks in spring and fall was present. Budd et al. (1995) utilized the Australian Bureau of Meteorology Global Atmospheric Assimilation and Prediction Scheme (GASP) for three years (1989–92) and achieved accumulation values very close to glaciological observation. Annual accumulation rates of  $157 \text{ mm yr}^{-1}$  were derived from the GASP model, compared to  $160 \text{ mm yr}^{-1}$  obtained from glaciological data. The GASP indicated a well-defined annual cycle for the whole of Antarctica, with larger amounts of precipitation occurring in winter. Accumulation values for the higher elevation regions of the interior had little or no annual trend. The results obtained by Yamazaki (1992) and Budd et al. (1995) suggest the viability of using numerical analyses to determine Antarctic net precipitation.

The moisture budget method has attracted attention within the last few years, and several studies are worth noting. In Bromwich (1988), coastal upper air station data were used to determine the local precipitation rates during one year for an arc-shaped section of East Ant-

arctica. Spatial coverage provided by station arrays is quite good along the coast. The southern boundary was located along the ridge of the interior ice sheet, where the transports are mostly small. A close match was achieved between atmospherically derived accumulation values for 1972 with multiannual glaciological results. Results were reliable for seasonal timescales and for areas of at least  $10^6 \text{ km}^2$ . This technique has been expanded upon by Connolley and King (1993) and Bromwich and Robasky (1993). In Connolley and King (1993), the moisture budget approach was employed using Antarctic rawinsonde data obtained from the Global Telecommunications System (GTS). In Bromwich and Robasky (1993), results obtained by Connolley and King were shown to be in close agreement with Bromwich (1988), with the inclusion of the western boundary moisture transport and synthetic data from the Roi Baudouin station. The latter result arises because of the large spatial variability associated with meridional moisture transport along the East Antarctic coast.

An ancillary benefit of using the atmospheric analyses in computing Antarctic net precipitation is a depiction of the atmospheric moisture transports. The study of Southern Hemisphere moisture fluxes is an essential component to the improvement of numerical weather forecasts and general circulation models (GCMs). Several previous studies of moisture transports using rawinsonde and numerical analyses are worth mentioning. Peixoto and Oort (1983) used global upper air station data for zonal transport estimates over a 10-yr (1963–73) period. Although the near-zonal station coverage along the coast of East Antarctica is reasonable, there are significant gaps in West Antarctica, particularly in the South Pacific sector. Howarth (1983) and Howarth and Rayner (1986) conducted moisture budget studies for the Southern Hemisphere using objective analyses provided by the Australian Bureau of Meteorology for the years 1973–78 and 1980–84. Masuda (1990) investigated the analyses from the ECMWF over a 1-yr period (1979) and is probably the best available global dataset of atmospheric moisture fluxes. Table 1 provides a list of several other studies and their duration.

TABLE 1. Studies of Southern Hemisphere moisture fluxes.

	Dataset time period
Based on atmospheric data	
Starr et al. (1969)	1958
Peixoto and Oort (1983)	1963–73
Howarth (1983), Howarth and Rayner (1986)	1973–78, 1980–84
Based on surface data	
Sellers (1965)	multiyear
Baumgartner and Reichel (1975)	multiyear
Korzoun et al. (1977a,b)	multiyear

Section 2 describes the analyses, the approach used in computing moisture transports and net precipitation, and rawinsonde validation methods. In section 3, results obtained from a comparison of the numerical analyses to Macquarie Island and Antarctic rawinsonde data are presented. A comparison of moisture transports over the Southern Ocean and Antarctica with studies listed in Table 1 is given in section 4. Areal averaged Antarctic net precipitation is presented in section 5, and a summary of results is provided in section 6.

## 2. Approach

### a. Analyses description

The analyses used in this study were obtained from the National Center for Atmospheric Research (NCAR) and the Australian Bureau of Meteorology. The ECMWF and NMC analyses are reported twice daily (0000 and 1200 UTC) on a  $2.5^\circ$  latitude-longitude grid. ABM analyses are reported twice daily (1100 and 2300 UTC) and are held on a  $47 \times 47$  polar stereographic grid of the Southern Hemisphere. The ABM analyses are translated onto the  $2.5^\circ \times 2.5^\circ$  grid to conform with the other two analyses for the comparison of moisture fluxes. Both the ECMWF and the NMC analyses report wind data at 14 standard levels to 10 hPa, and moisture values at 6 standard levels to 300 hPa. ABM wind data is reported at 7 standard pressure levels, and moisture data at 4 standard levels to 500 hPa.

A major disadvantage to using numerical analyses for climatic study is the effect of alterations in the data assimilation system on the climatic ensemble of analyses (Trenberth 1992). The expressed primary intent of the analyses is for operational weather forecasting purposes, which require the best objective analyses possible. Hence, it becomes difficult to discern real climatic change from analysis modifications. Documentation of these changes is not always complete (Trenberth 1992). Climatic biases, not directly affecting the operational purpose of the analyses, may also be present. Clearly, it is not possible to assess the impact of all the alterations made to the analyses during the 8-yr period examined here. Analyses produced by the operational weather centers nevertheless represent the most comprehensive assimilation of meteorological data available.

The ECMWF analyses are produced from four-dimensional data assimilation, incorporating data over a 6-h period, combined with a 6-h "initial guess" provided by the ECMWF medium-range weather forecasting model (Bengtsson et al. 1982; Hollingsworth et al. 1986; Trenberth 1992). On 1 May 1985, the ECMWF resolution was increased to T106 (triangular truncation at wavenumber 106). Substantial changes were also made to physical parameterizations on this date that affect both the wind and moisture fields.

The NMC analyses are produced in a fashion similar to the ECMWF analyses. The data assimilation system, known as the Global Data Assimilation System (GDAS) (Trenberth and Olson 1988c; Kanamitsu 1989; Bonner 1989; Kalnay et al. 1990), has evolved considerably over the last several years. On 28 May 1986, resolution increased from 12-layer, R24 (rhomboidal truncation) to 18-layer, R40, and many changes were made to physical parameterizations. These changes to the ECMWF and NMC physical parameterizations are obvious in time series.

The ABM analyses are produced through the incorporation of manually prepared analyses into a first-guess field produced by a numerical prognosis model (Smagorinsky et al. 1965). The standardized analyses comprise surface and upper-air data, observations from ships and aircraft, and satellite-derived information. The analysis procedure is described by Howarth (1983), Le Marshall et al. (1985), and Karoly and Oort (1987). There has been no published list of changes to the analysis scheme; in 1989 the analysis system was changed to a global spectral model with improved physics and R31 horizontal resolution (Bourke et al. 1991). In the past, the ABM analyses have been considered one of the better hemispheric datasets available (Trenberth 1979). A major disadvantage to the ABM analysis is the lack of moisture data above the 500-hPa level. No correction was made for this, since it gives a true representation of the difficulties in using this analysis for this study.

### b. Moisture flux and convergence calculations

The total moisture flux is computed at each pressure level as the product of specific humidity and horizontal wind vector. These transports are divided into mean and eddy components such that

$$\text{Tr} = \underbrace{\bar{q}\bar{\mathbf{V}}}_A + \underbrace{\bar{q}'\bar{\mathbf{V}}'}_B + \underbrace{\bar{q}'\bar{\mathbf{V}}'}_C, \quad (1)$$

where  $q$  is the specific humidity,  $\mathbf{V}$  is the wind vector, the overbar denotes temporal averaging, and the superscript prime denotes the eddy component. Thus terms A, B, and C represent total, mean, and eddy transports, respectively. Meridional and zonal transport terms are time-averaged for monthly and annual time periods at each standard pressure level. The fluxes are then vertically integrated using

$$\mathbf{Q} = \int_{P_0}^{P_{\text{stc}}} \frac{\text{Tr}}{g} dp, \quad (2)$$

where  $\mathbf{Q}$  is the vertically integrated transport,  $P_{\text{stc}}$  is the average surface pressure,  $P_0$  is the effective pressure at the top of the atmosphere (if different than zero),  $\text{Tr}$  is the transport vector, and  $g$  is gravitational acceleration. Precipitable water  $W$  is found using

$$W = \int_{P_0}^{P_{\text{sfc}}} \frac{q}{g} dp. \quad (3)$$

The integration is performed using the trapezoidal rule.

Difficulties arise in the determination of the surface value, a crucial issue for Antarctica. The ECMWF dataset contains surface values for temperature and pressure, 2-m values for temperature and dewpoint, and 10-m values for horizontal wind. The NMC dataset contains surface pressure and temperature and boundary layer values for relative humidity, wind components, and potential temperature. Boundary layer values are valid at 200 m prior to April 1985 and at 40 m thereafter. The ABM dataset is reported only at standard pressure levels. For consistency and to minimize incompatibility among the three analyses, surface values are interpolated using

$$C_{\text{sfc}} = \begin{cases} C_1 + \frac{(C_2 - C_1)(P_{\text{sfc}} - P_1)}{P_2 - P_1}, & P_{\text{sfc}} < 1000 \text{ hPa} \\ C_{1000} + \frac{(C_{850} - C_{1000})(P_{\text{sfc}} - P_{1000})}{P_{850} - P_{1000}}, & P_{\text{sfc}} > 1000 \text{ hPa}, \end{cases} \quad (4)$$

where  $C$  is the variable of interest and  $P$  is pressure. Subscript 1 corresponds to the level just below the surface, 2 corresponds to the level above, and 850 and 1000 denote pressure levels (hPa). A climatic surface pressure map is sufficient for annual averages and is used here (ECMWF 1992 annual average). For timescales of less than 1 year, surface pressure variations are significant (e.g., Schwerdtfeger and Prohaska 1956; van Loon 1972). Unless otherwise provided by the analysis, surface pressure is calculated using (Trenberth 1992):

$$P_{\text{sfc}} = P_{1000} \exp \left[ \frac{(Z_{1000} - Z_{\text{sfc}})g}{RT_v} \right], \quad Z_{\text{sfc}} < Z_{1000}$$

$$\ln \left( \frac{P_{\text{sfc}}}{P_1} \right) = \ln \left( \frac{P_2}{P_1} \right) \left( \frac{Z_{\text{sfc}} - Z_1}{Z_2 - Z_1} \right), \quad Z_{\text{sfc}} > Z_{1000}, \quad (5)$$

where  $Z$  is the geopotential height,  $R$  is the gas constant, and  $T_v$  is the virtual temperature at 1000 hPa.

The atmospheric moisture balance equation is expressed as

$$-\underbrace{\left\langle \frac{d\bar{W}}{dt} \right\rangle}_A - \underbrace{\langle \nabla \cdot \mathbf{Q} \rangle}_B + \underbrace{\langle \nabla \cdot \mathbf{Q}_{\text{corr}} \rangle}_C = \langle P - E \rangle, \quad (6)$$

where angle brackets indicate an areal average, term A is the time rate of change of total water vapor stored in the atmospheric column (hereafter referred to as the storage term), term B is the horizontal moisture outflow through the specified region's lateral boundary, and C

represents a mass balance correction. Previous study has found the storage term to be small over annual time periods (Bromwich 1988) and is calculated only for interannual time periods. Term B may be rewritten as the following line integral around the border of the area in question (Bromwich and Robasky 1993):

$$\langle \nabla \cdot \mathbf{Q} \rangle = -\frac{1}{A} \oint \left\{ \int_0^{P_{\text{sfc}}} \frac{q\bar{V}}{g} dp \right\} \cdot \mathbf{n} dl, \quad (7)$$

where  $A$  is the area over which the net precipitation is to be determined, and  $\mathbf{n}$  is the outward normal to the area perimeter. It is easily seen that the determination of net precipitation south of a given latitude becomes a trivial calculation for a gridded dataset. The boundary of Antarctica may be approximated by the connection of grid points, as in Fig. 1.

Term C represents the correction necessary for the conservation of dry air within an atmospheric column. This term may not be solved for directly but must be treated by correcting the original velocity field. A strategy for correcting mass balance in the analyses has been outlined by Trenberth (1991). A residual term may be calculated from the columnar mass balance:

$$\left( \frac{\partial P_{\text{sfc}}}{\partial t} - g \frac{\partial W}{\partial t} \right) + \nabla \cdot \int_{P_0}^{P_{\text{sfc}}} (1 - q) \mathbf{V}' dp = R, \quad (8)$$

where  $\mathbf{V}'$  is the original velocity field. A corrected velocity field  $\mathbf{V}^c$  is found by

$$\mathbf{V}^c = \nabla \chi (P_{\text{sfc}} - P_0 - gW)^{-1}, \quad (9)$$

where  $\chi$  is a potential function defined such that

$$\chi = \nabla^{-2} R. \quad (10)$$

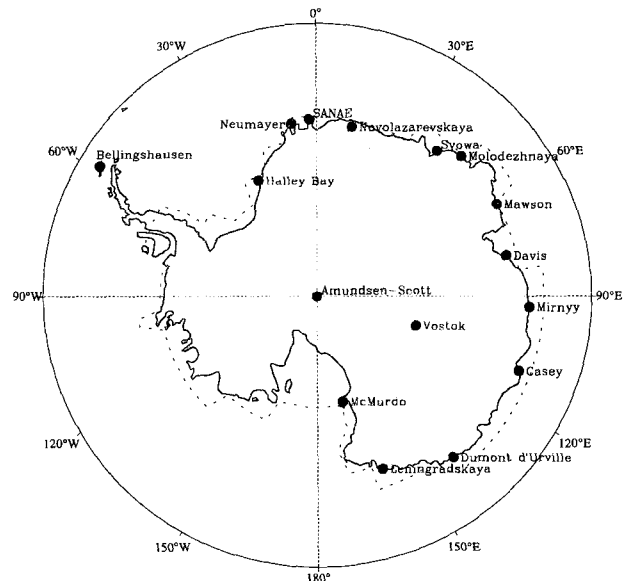


FIG. 1. Schematic of wall used to determine Antarctic moisture convergence (dashed line) and rawinsonde stations comprising the GTS dataset.

The impact of this correction on ECMWF net precipitation for 1986 has been assessed. The resulting impact on computed net precipitation is typically less than  $1 \text{ cm yr}^{-1}$ , or about 6% of the estimated Antarctic net precipitation. The impact of mass balance corrections to the velocity field has previously been found to be small, usually on the order of a few centimeters per second (Trenberth et al. 1995). The procedure is computationally expensive, however, and was not applied for this study.

### c. Sounding validation

Moisture fluxes calculated from numerical analyses are evaluated against rawinsonde observations from Antarctica and Macquarie Island. The Macquarie Island station was obtained from the Australian Bureau of Meteorology and provides a long-term record (1985–92) for comparison in the Southern Ocean. Antarctic rawinsonde stations are listed in Table 2. These soundings were obtained from the GTS for the period 1988–89 and provided by British Antarctic Survey.

In the vertical, the moisture fluxes from the rawinsondes are available at many standard levels and a variable number of significant levels. Each sounding is interpolated to levels at every 50 hPa and then time-averaged. The interpolation is performed so that the sounding profiles may be time-averaged and compared to analyses profiles. The 50-hPa interval selected is not arbitrary; Bromwich (1979) investigated the katabatic-prone Mirnyy station and determined this interval accurately evaluates the time-averaged integrated transport.

For the comparison to sounding data at Macquarie Island, the gridded numerical analyses data are interpolated to the sounding location. Over the steep terrain of the Antarctic coastline, the nearest four analysis grid points are surveyed; the grid point with the surface pressure nearest to that of the station is used.

In evaluating the analyses, two criteria are noted. One is the reproducibility, or the incorporation of the sounding data into the analyses. This can be verified through the comparison of vertical profiles of moisture transport. The second criterion is the adequacy of the vertical resolution afforded by the analyses, which may not be adequate to resolve the moisture flux maximum in the lower troposphere (Rasmusson 1977). This may be evaluated by an examination of the vertically integrated transports. It is worth noting that in the context of the second criterion, the phrase “analysis deficiency” does not necessarily correspond to inaccuracies of the data assimilation systems for the analyses, but rather the failure in the assumption that the vertical integration of standard-level quantities reasonably provides the same accuracy as the vertical integration of a multilevel rawinsonde.

A vital component of the evaluation is the legitimacy of the sounding data. The Antarctic rawinsonde record

TABLE 2. List of Antarctic rawinsonde stations obtained from the GTS for 1988–89, after Connolley and King (1993). Stations used in the East Antarctic moisture convergence calculation shown in Fig. 9 are indicated by asterisks.

Station name	Latitude	Longitude	Reporting protocol
Bellingshausen	62.20°S	59.93°W	Once daily.
Halley Bay	75.50°S	26.65°W	Once daily.
Neumayer	70.62°S	8.37°W	Once daily.
SANAE*	70.30°S	2.35°W	Twice daily.
Novolazarevskaya*	70.77°S	11.83°E	Once daily, twice daily in summer.
Syowa*	69.00°S	39.58°E	Twice daily.
Molodezhnaya*	67.67°S	45.85°E	Twice daily.
Mawson*	67.60°S	62.87°E	Once daily.
Davis*	68.57°S	77.95°E	Once daily.
Mirnyy*	66.55°S	93.02°E	Once daily, twice daily in summer.
Casey*	66.28°S	110.52°E	Once daily.
Dumont d'Urville	66.67°S	140.02°E	Once daily.
Leningradskaya	69.50°S	159.38°E	Once daily.
McMurdo	77.85°S	166.67°E	Once daily, twice daily in summer.
Amundsen-Scott	90.00°S	—	Once daily, twice daily in summer.
Vostok*	78.45°S	106.87°E	Once daily, twice daily in summer.

has been used as a benchmark for previous moisture flux studies and represents the only source of “ground truth” available. There are well-known problems with the accuracy of sounding humidity measurements for cold conditions (e.g., Elliott and Gaffen 1991; Schmidlin 1994). Connolley and King (1993) estimate their fluxes to have an uncertainty of 20%, with the dominant contribution coming from moisture measurement uncertainties. It has been suggested that several factors conspire to reduce uncertainty for these soundings, however (Bromwich and Robasky 1993). Many of the Antarctic stations are coastal, where relatively warm conditions prevail and inversions are less likely (Phillip and Zillman 1970). Additionally, the vast majority of the observed moisture transport is associated with storms of comparatively warmer conditions. Also, significant cancellation of systematic error is expected (Bromwich and Robasky 1993). In the detailed study of Arpe and Cattle (1993), it was shown that large discrepancies between observations and analyses at a particular location along the East Antarctic coast are possible. While an exercise in station-by-station comparison is performed, an alternative comparison is also made between the moisture convergence computed by the analyses and that computed from the rawinsonde data, which is well documented (Bromwich 1988; Bromwich and Robasky 1993). Comparisons of Antarctic moisture convergence with previously documented multiannual accumulation values (e.g., Giovinetto and Bentley 1985) are also fundamental in determining validity.

### 3. Sounding data comparison

#### a. Macquarie Island

Macquarie Island is located at 54.5°S, due south of Tasmania. An average of 81% of the possible twice-daily soundings were actually recorded for the 8-yr period in question. In Fig. 2, a comparison between observational and analysis specific humidity profiles is shown, averaged for 1986 (a) and 1990 (b). In general, agreement is quite reasonable for a given annual sounding of specific humidity. Not reproduced, a plot of the 12-month running mean vertically integrated precipitable water shows the ECMWF being larger than observed for 1985 and 1986 by approximately 15%–20%, a feature readily apparent in Fig. 2a. It appears that the NMC analyses are generally the best of the three analyses for comparisons of atmospheric moisture content. The ABM analyses are typically low by about 15%. This results from inaccuracies in the 1000-hPa value, and the unavailability of data at levels higher than 500 hPa, which detracts somewhat from their usefulness.

In Fig. 3, annually averaged (a,b) meridional and (c,d) zonal transports are similarly compared for 1986 and 1990. Several significant features are evident in the meridional transport. In the 1986 analyses, it is clear that the southward transport in both the ECMWF and NMC analyses exceed observed values, essentially at all levels. In the 1990 profile, the observed and analyzed transports have moved closer together. This may be more easily seen in the vertically integrated merid-

ional quantities shown in Fig. 4a. As seen in Fig. 3, the rawinsonde data lack surface values for several years including 1986. Rawinsonde values are extrapolated to the surface for the vertical integration. Prior to calendar year 1987, vertically integrated analyses values of ECMWF and NMC were overestimating the observed transport by approximately 30%–40%. The meridional transport of the ABM analysis is in rough parity with observations for 1985 and 1986. For the 12-month running means beginning January 1987, observed and analyzed values of the ECMWF and NMC became approximately equal; values of the ABM analyses after 1988 underestimate the observed values by roughly a factor of 2. This may result from changes to the NMC analysis scheme during 1986. Particularly striking is the agreement between these two analyses for the entire period. The ABM analysis appears to narrow some of the difference between itself and the other two analyses. The overall trend of the other two analyses and even some of the subtle variations appear to be reproduced by the ABM. Decomposition of the meridional transport into mean and eddy components indicates that the vast majority of the disagreement after January 1987 results from inaccuracies, usually an underestimation, in the ABM eddy transport.

In Fig. 4b the zonal quantities for Macquarie Island show somewhat similar trends in agreement. Analysis values from the ECMWF and NMC appear to converge with the observational values for the 12-month mean beginning in April 1986, earlier than for the meridional transport. Agreement between these two analyses is ev-

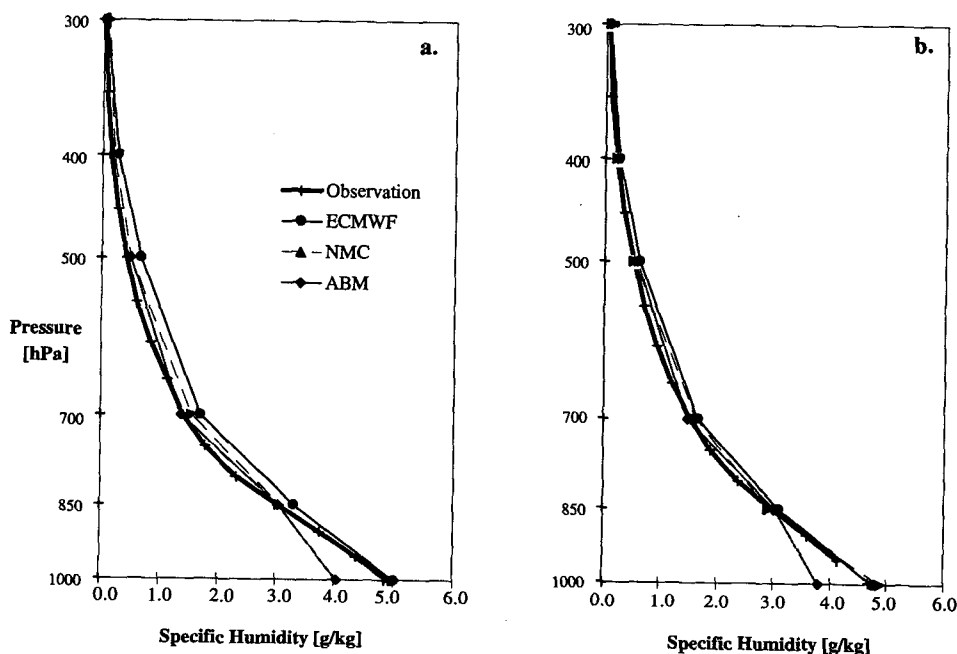


FIG. 2. Comparison of annually averaged specific humidity profiles for (a) 1986 and (b) 1990 for Macquarie Island.

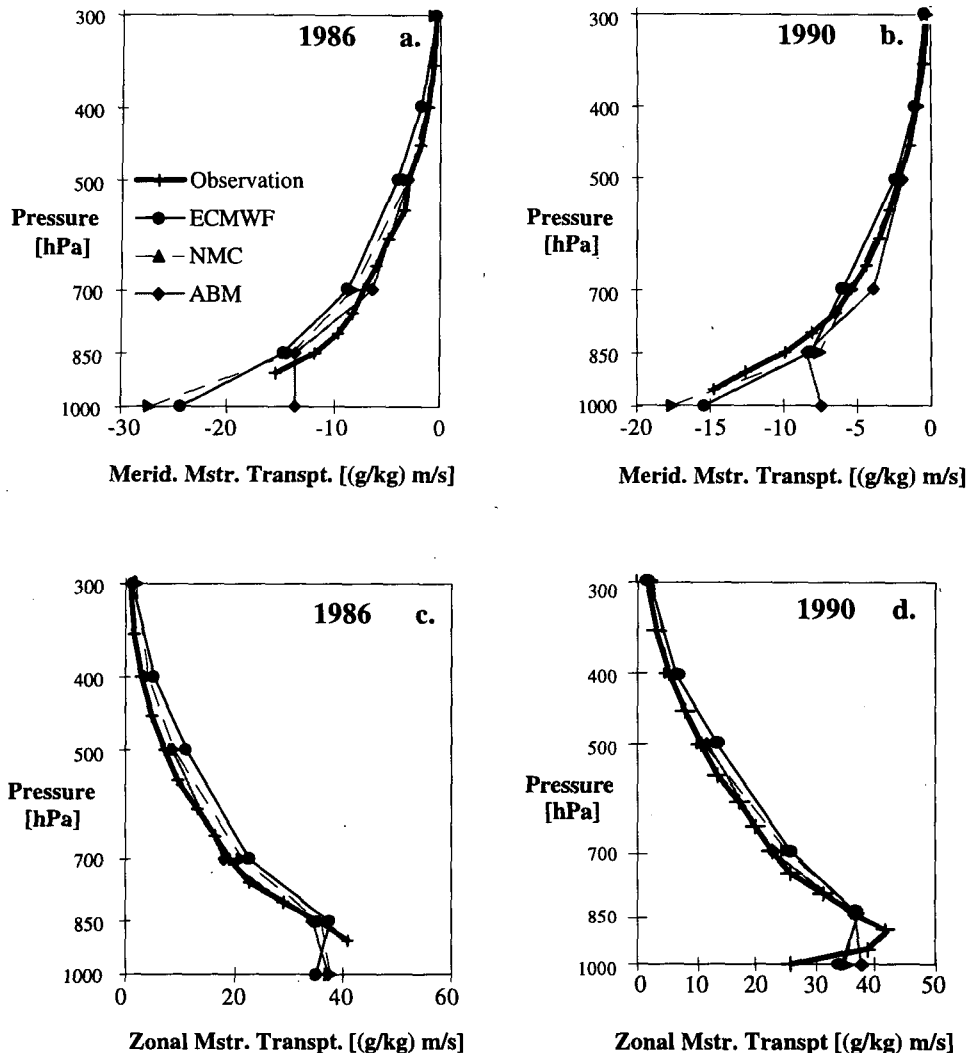


FIG. 3. Comparison of annually averaged (a), (b) meridional and (c), (d) zonal moisture transport profiles for 1986 and 1990 for Macquarie Island.

ident, although not as close as for the north-south transport. The ABM analysis underestimates the transport by about 10%. Again, there appears to be an overall agreement in the trend between the three analyses. The observed oscillation in the zonal data is qualitatively reproduced in the analyses, though the 1986 minimum is approximately four months late. In examining the vertical distribution of the zonal transport in Figs. 3c and 3d, it can be seen that a trade-off is occurring at upper levels that accommodates the intricate profile at lower levels. In particular, there are difficulties in resolving the transport maximum at 900 hPa using analyses. In this context, the agreement of the vertically integrated values is quite good.

For Macquarie Island, the analyses are able to qualitatively reproduce the interannual variability in the soundings and are in close agreement quantitatively af-

ter January 1987. The ability of the analyses to reproduce the vertical distribution of the transport is significantly hindered by their limited resolution at low levels. From a comparison of the vertically integrated quantities, however, it happens that trade-offs occur at various levels to inadvertently produce a more accurate result through error cancellation.

#### b. Antarctic rawinsonde comparison

As was alluded to previously, agreement between soundings and analyses was expected to be close for Macquarie Island because of the comparative lack of orographic effects. Complex orography, highly localized wind phenomena, rapid spatial changes in wind direction and magnitude, and reporting difficulties in East Antarctica produce a particularly difficult challenge for the analyses.

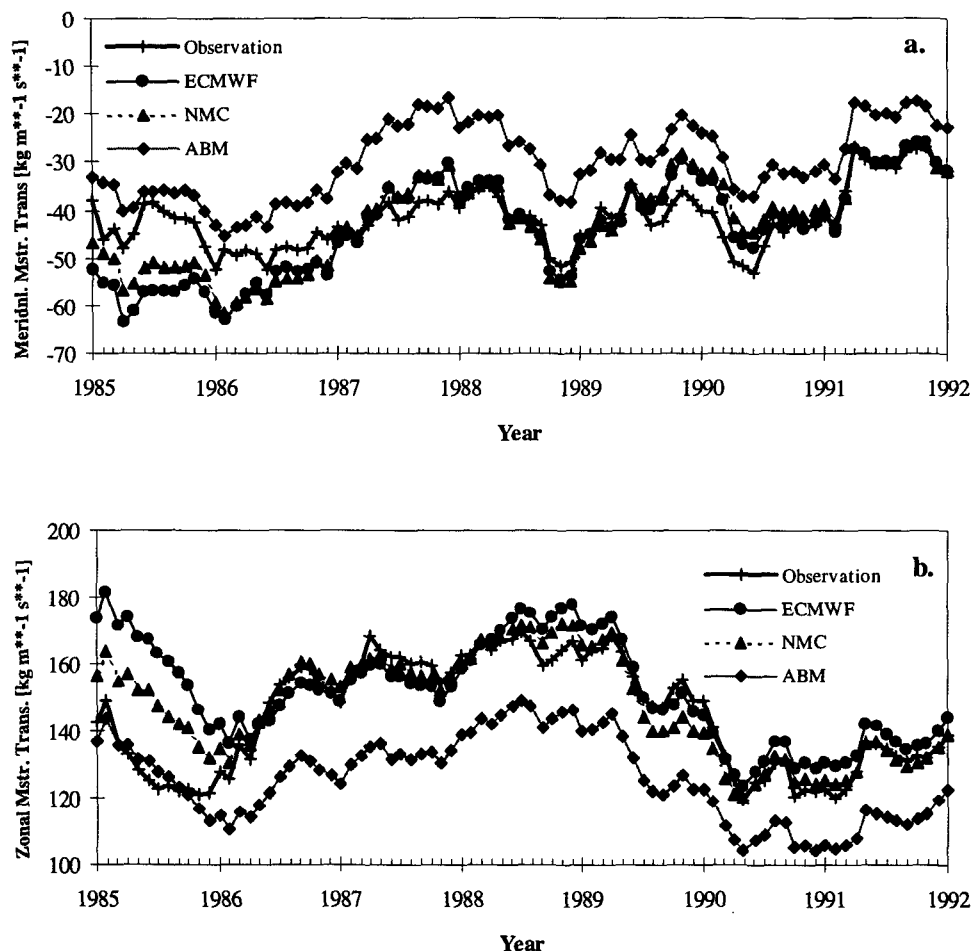


FIG. 4. Comparison of vertically integrated (a) meridional and (b) zonal 12-month running mean moisture transports ( $\text{kg m}^{-1} \text{s}^{-1}$ ) for Macquarie Island. Dates correspond to the beginning of each 12-month average.

In general, the station-by-station moisture flux comparison of analyses to Antarctic sounding data may be characterized as a mixed bag. The skill of the analyses at each level is highly variable, depending on the station. Significant error cancellation occurs between stations, however. In Figs. 5 and 6, vertical profiles of zonally averaged East Antarctic coastal rawinsonde (a) specific humidity and (b,c) moisture fluxes are shown for 1989 in comparison with the fluxes derived from the three analyses. The average shown for Fig. 5 is taken from  $9^{\circ}\text{W}$  to  $45^{\circ}\text{E}$ , encompassing five stations. Figure 6 encompasses six stations between  $62^{\circ}$  and  $160^{\circ}\text{E}$ . In Fig. 5a, it is seen that the ECMWF specific humidity is significantly greater than the observed values, particularly at the lower levels. At the surface, the ECMWF exceeds the observed value by slightly more than 50%. The NMC and ABM analyses by contrast are in near parity with observation. In Fig. 6a the error is somewhat larger, indicating a deterioration in the accuracy of the analyses as the comparison progresses eastward. This is particularly true with the NMC anal-

yses at lower levels. Specific humidity values for NMC near the surface approach the error found in the ECMWF analyses. In Fig. 5b, the observed meridional transport shows a marked low-level outflow associated with the katabatic wind regime capped by inflow. The ability of the ECMWF analyses to simulate the low-level transport is remarkable. Agreement is within  $0.03 \text{ g kg}^{-1} \text{ m s}^{-1}$ . In contrast to the ECMWF, the NMC analyses significantly underestimate both the low-level outflow and the inflow maximum at 850 hPa. In Fig. 6b, there again appears to be a decrease in the accuracy of the analyses, particularly at the 850-hPa level. The ECMWF value is almost four times the value observed. Again, however, the surface value appears to be well represented by the ECMWF. In Fig. 5c, the zonal transport is again accurately reproduced by the ECMWF at the low levels. The NMC and ABM analyses both underestimate the zonal transport near the surface. At 850 hPa, the NMC and ABM analyses underestimate the transport magnitude by an average of 20%.



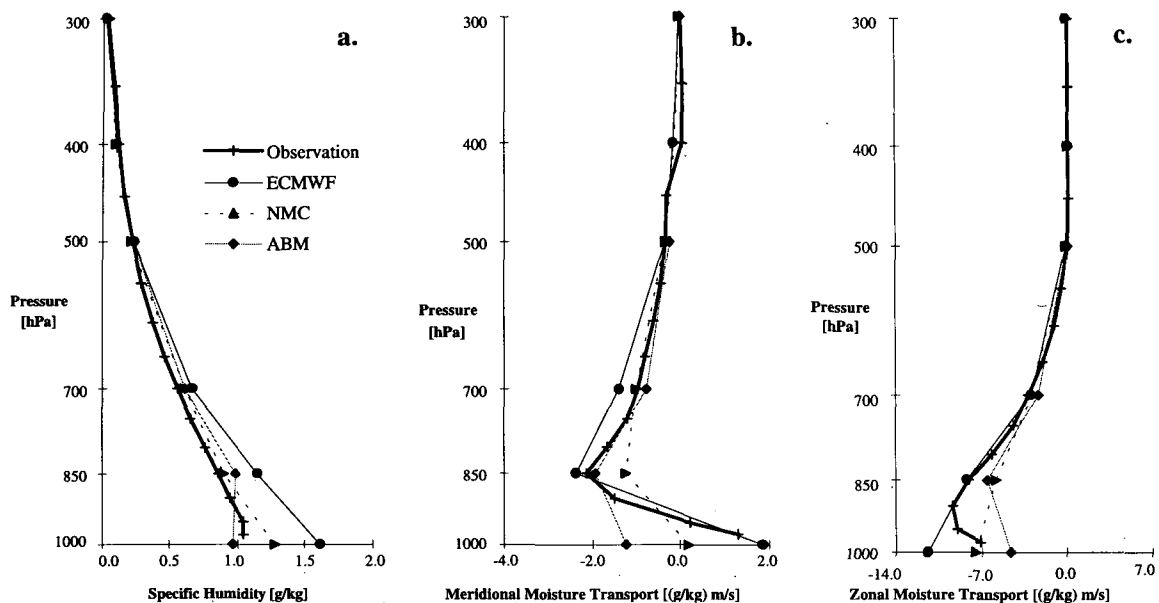


FIG. 5. Comparison of annually averaged 1989 Antarctic vertical profiles of (a) specific humidity ( $\text{g kg}^{-1}$ ), (b) meridional moisture transport ( $\text{g kg}^{-1} \text{ m s}^{-1}$ ), and (c) zonal moisture transport ( $\text{g kg}^{-1} \text{ m s}^{-1}$ ), zonally averaged between  $9^\circ\text{W}$  and  $45^\circ\text{E}$ .

When vertically integrated, the ECMWF precipitable water significantly exceeds the observed value by almost 30% for the average sounding depicted in Fig. 5a. Both the NMC and ABM precipitable water values are within 7% of the value determined by observation. Despite the ability of the ECMWF analyses to reproduce the lowest levels of the meridional transport, the vertically integrated transport value is less accurate than the other analyses. The southward moisture trans-

port observed from  $9^\circ\text{W}$  to  $45^\circ\text{E}$  is  $4.8 \text{ kg m}^{-1} \text{ s}^{-1}$ ; the ECMWF value is  $5.8 \text{ kg m}^{-1} \text{ s}^{-1}$ ; NMC,  $4.2 \text{ kg m}^{-1} \text{ s}^{-1}$ ; and ABM,  $5.2 \text{ kg m}^{-1} \text{ s}^{-1}$ . This is due largely to the inaccuracy of the ECMWF analyses at the 700-hPa level. The values of the other two analyses are closer to the observed value due to vertical error cancellation. For the zonal transport, the ECMWF is within 3% of the observed value, while the NMC and ABM analyses are an average of 20% too low. Each of

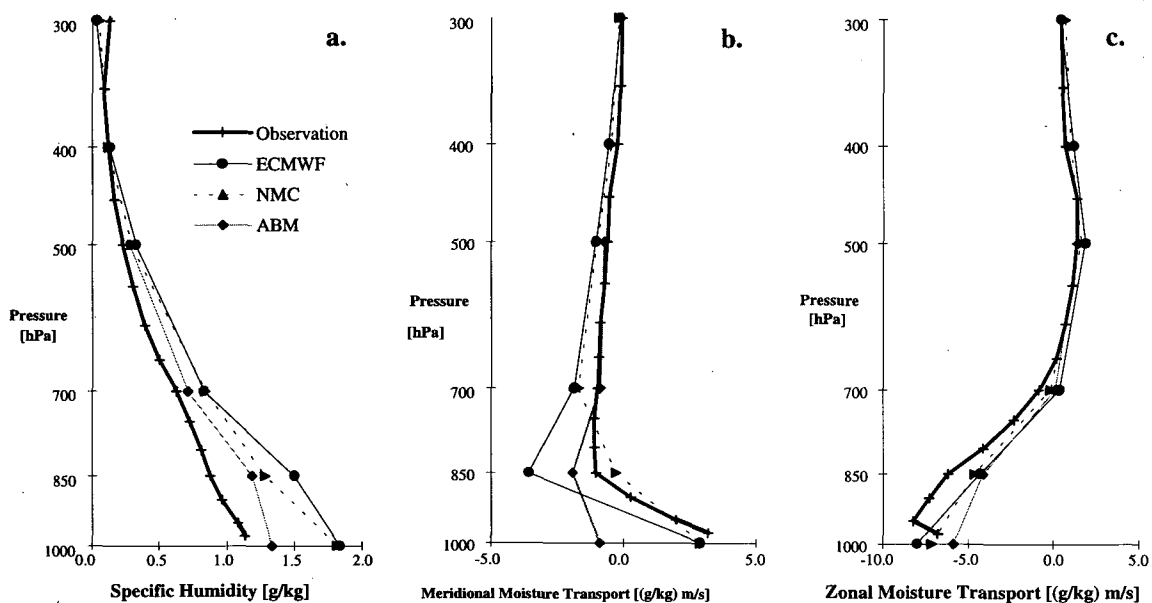


FIG. 6. Same as Fig. 5 but zonally averaged between  $62^\circ$  and  $160^\circ\text{E}$ .

these results is dependent on the station and the intricacies of the sounding profile.

Time series plots of the vertically integrated precipitable water and moisture fluxes are shown for individual stations in Figs. 7 and 8. Again the results are highly variable, depending on the station. The ECMWF analyses are seen to consistently overestimate the observed precipitable water. This overestimation is largest for stations farther east. At Dumont d'Urville, for example, ECMWF precipitable water is overestimated by approximately 40% (not shown); by contrast, ECMWF and observed precipitable water values are in near

agreement for SANAE. ABM analyses consistently underestimate precipitable water by a small margin. Temporally, the largest differences in the analyses occur during the precipitable water maxima in the austral summer months. From Fig. 8, it may be seen that the analyses zonal transports are somewhat superior to the meridional. This is not surprising given the magnitudes and the lack of variability in the zonal wind.

A particularly useful tool for evaluating the vertically integrated quantities is the previously mentioned moisture convergence calculations performed by Bromwich (1988, 1990) for the sector  $68.4^{\circ}$ – $76.8^{\circ}$ S,

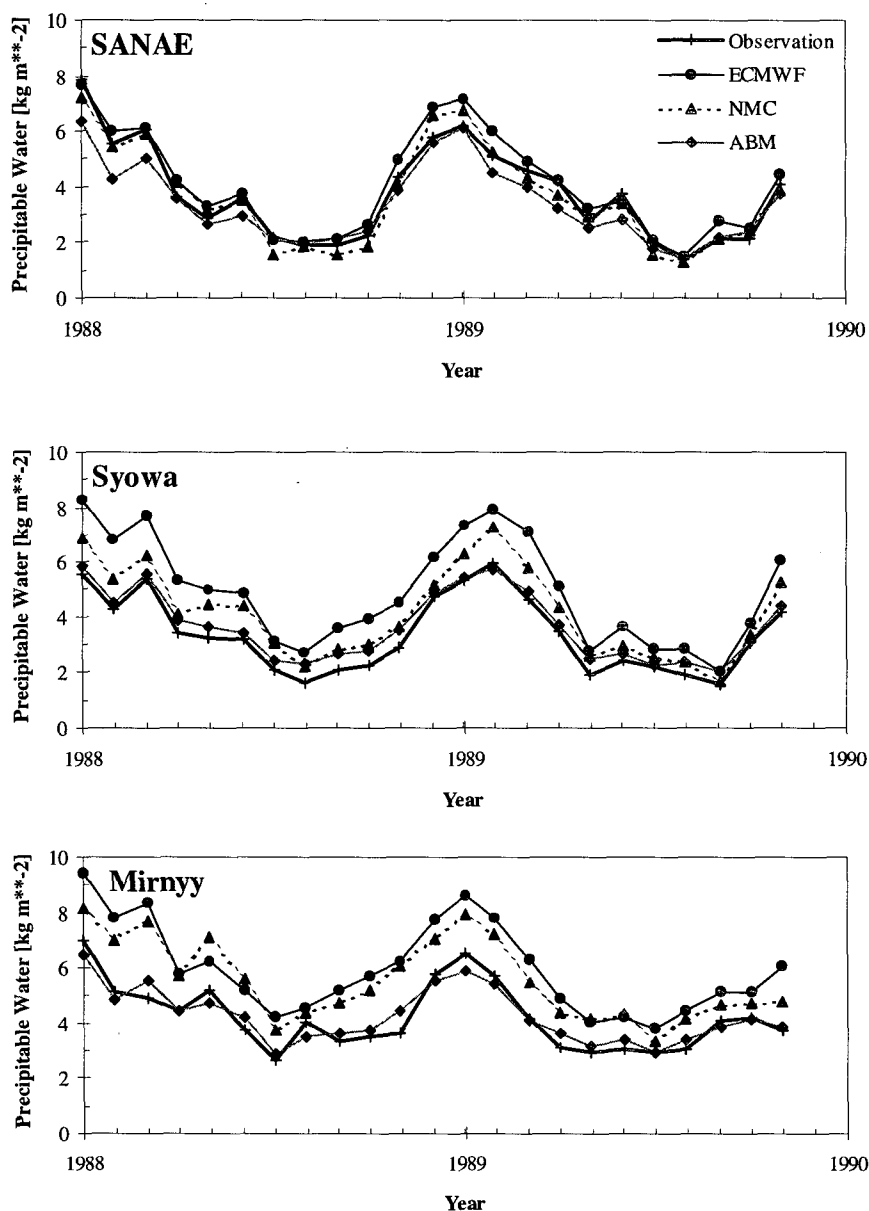


FIG. 7. Time series comparison of monthly averaged precipitable water ( $\text{kg m}^{-2}$ ) for three East Antarctic stations.

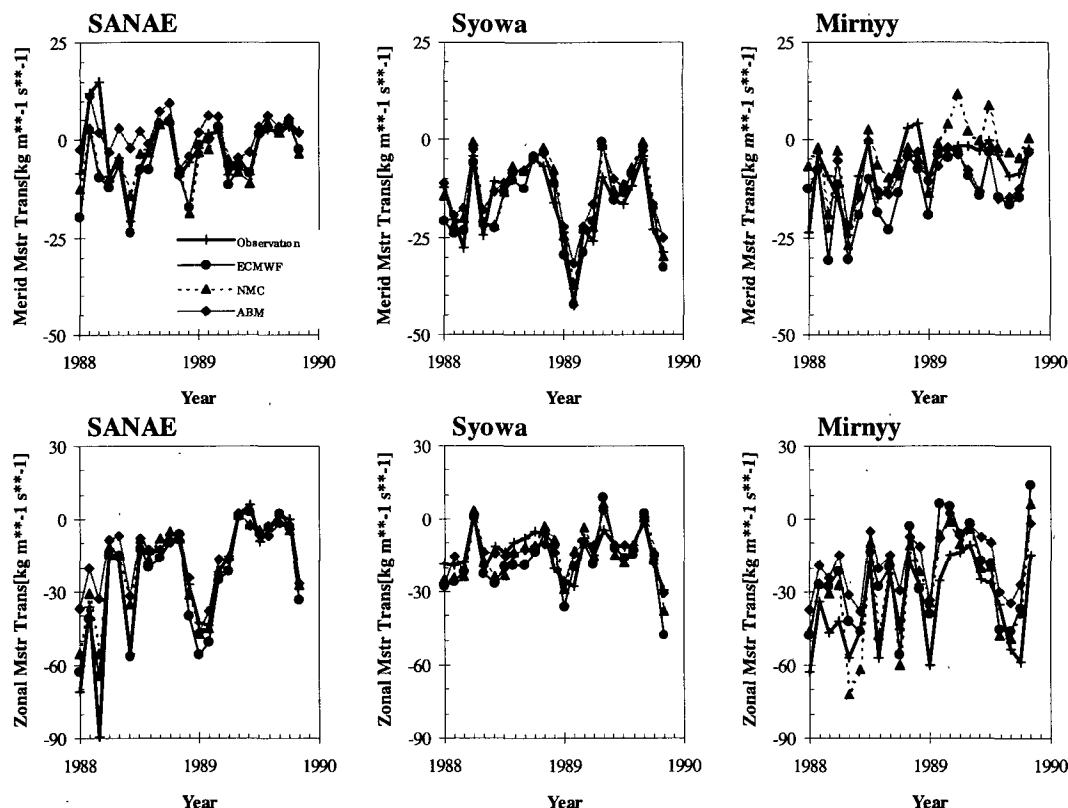


FIG. 8. Time series comparison for monthly averages of (a) meridional and (b) zonal vertically integrated moisture transports ( $\text{kg m}^{-1} \text{s}^{-1}$ ) for Antarctic stations.

$0^{\circ}$ – $110^{\circ}\text{E}$ . The sector was constructed to take advantage of the well-sampled coastal section of East Antarctica. The transports across the eastern, western, and northern boundaries are estimated from available rawinsonde data. Along the southern boundary, the influence of the interior Vostok station is applied to a 300-km radius from the station. Along the remainder of the southern boundary the transports are assumed to be negligible. The method implemented here is not as rigorous as that outlined in Bromwich (1988), which combined the available rawinsonde data with climatological data given by Taljaard et al. (1969) and Jenne et al. (1971); an adequate basis for comparison is provided, however. The calculation for the analyses data is performed in a manner identical to that used for the soundings: that is, analyses profiles representative of each individual station are used to calculate the moisture convergence rather than utilizing the full horizontal resolution of the analyses. This is done to produce an unbiased comparison. Figure 9a depicts the 12-month running mean comparison for the two years of sounding data available. The observed 2-yr average of  $106 \text{ mm yr}^{-1}$  is very close to values previously determined from atmospheric and surface-based observations. Bromwich (1990) determined a value of  $105 \text{ mm yr}^{-1}$  using rawinsonde observations for 1972.

Bromwich and Robasky (1993) computed a value of  $108 \text{ mm yr}^{-1}$  for 1980–82 and 1988–90, derived from Connolley and King (1993). The long time accumulation value, derived from Giovinetto and Bentley (1985), is  $108 \text{ mm yr}^{-1}$  (Bromwich 1990). In Fig. 9a the ECMWF analysis is within  $4 \text{ mm yr}^{-1}$  of the observed 2-yr mean value and reasonably reproduces the observed interannual variation. The ABM analysis values are slightly larger than the observed values by an average of  $17 \text{ mm yr}^{-1}$ . The values produced by the NMC analysis are greatly deficient and in some cases approach zero for a 12-month average. In Fig. 9b, the meridional transports from coastal stations used in the convergence calculation are zonally averaged. The northern boundary meridional transport represents the largest contribution to the convergence calculation. The ECMWF analysis is again found to be very accurate at the surface level and at 850 hPa. A relatively small discrepancy of approximately  $0.5 \text{ g kg}^{-1} \text{ m s}^{-1}$  occurs at the 700-hPa level, apparently with little consequence for the vertically integrated value. In the ABM analyses, a trade-off is found to occur between the large discrepancies at the surface and the lack of values above the 500-hPa level. This trade-off produces moisture convergence values close to those observed despite a discrepancy of more than  $3 \text{ g kg}^{-1} \text{ m s}^{-1}$  at the surface

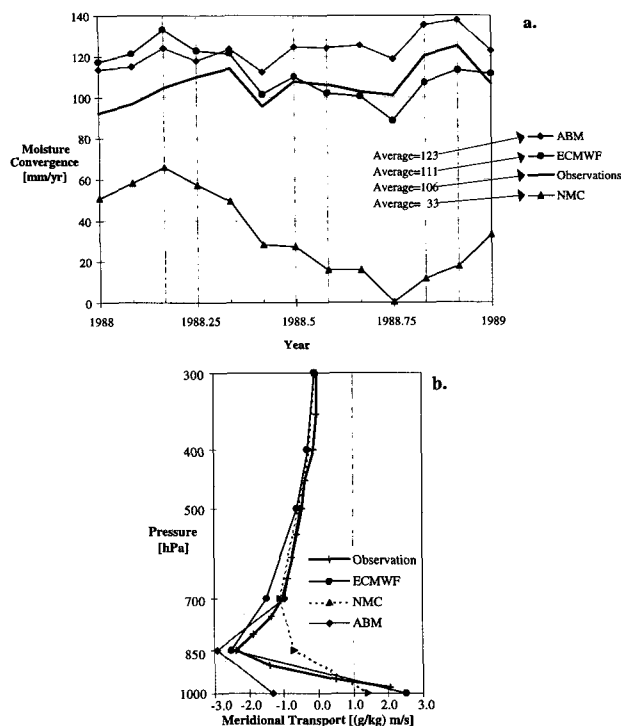


FIG. 9. (a) Comparison of East Antarctic moisture convergence ( $\text{mm yr}^{-1}$ ) across boundaries defined by Bromwich (1988) using 12-month running means. (b) Vertical profile of zonally averaged meridional moisture transport for coastal stations used in calculating East Antarctic moisture convergence ( $\text{g kg}^{-1} \text{m s}^{-1}$ ).

level. The NMC analysis only slightly underestimates the observed surface value and is reasonably close at many levels. However, the NMC analysis greatly underestimates the poleward flux at the critical 850-hPa level by approximately  $1.5 \text{ g kg}^{-1} \text{m s}^{-1}$ . It may be seen from Fig. 9b that this discrepancy greatly reduces the poleward transport exhibited in the complete pro-

file, thus producing the large error in the vertically integrated value. A comparison of Fig. 9b to zonally averaged profiles shown in Figs. 5b and 6b indicates that the NMC analysis is somewhat unlucky in the stations selected for the East Antarctic moisture convergence calculation; this again reflects the large variability in the skill of the analyses, depending on the station. The comparison nevertheless indicates the inability to reproduce observed station values at critical levels.

In summary, the comparison of the analyses to rawinsonde data produces somewhat mixed results. Generally, the ECMWF is clearly superior to the other analyses at each pressure level. The NMC and ABM analyses generally underestimate transport at each level, and vertical error cancellation may occur when inflow and outflow occur at different levels. Overall these results are not surprising given the coarse resolution and spectral nature of the analyses. The ability of the ECMWF to reproduce the observed moisture transport at each level is reassuring, and the comparison of East Antarctic moisture convergence demonstrates a high degree of reliability with this analysis.

#### 4. Southern Ocean moisture fluxes

Figure 10 provides a graphical comparison of the average net precipitation in  $10^\circ$  latitude bands calculated for the numerical analyses with the moisture flux studies listed in Table 1. Considerable disagreement was not altogether unexpected because of the diverse techniques employed and data available. In the region  $50^\circ\text{--}60^\circ\text{S}$ , though, values range from  $170 \text{ mm yr}^{-1}$  to more than  $750 \text{ mm yr}^{-1}$ . The general shape of the curve, however, is shared by the analyses and the other studies. For example, there is some agreement for values in the Antarctic interior ( $80^\circ\text{--}90^\circ\text{S}$ ), with values ranging from 25 to  $90 \text{ kg m}^{-2} \text{yr}^{-1}$ . Also, there is almost universal agreement that the zero point, defining the boundary between the subtropical moisture source

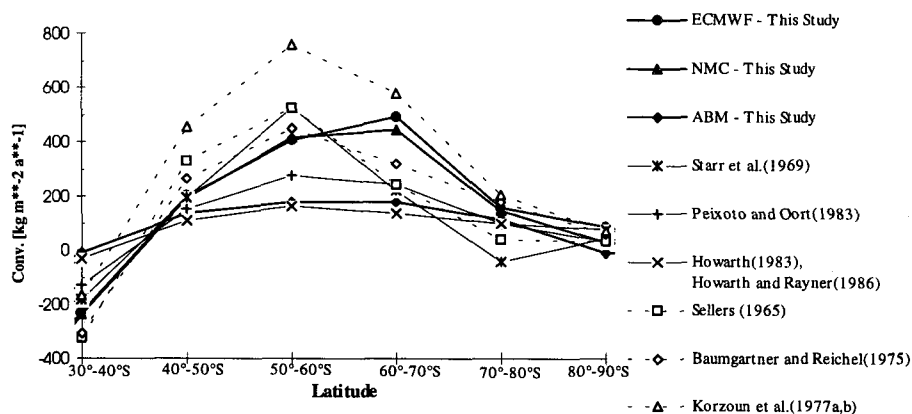


FIG. 10. Moisture transport convergence ( $\text{kg m}^{-2} \text{yr}^{-1}$ ) for  $10^\circ$  latitude bands in the Southern Hemisphere obtained from the numerical analyses long-term average in comparison to previous studies ( $\text{kg m}^{-2} \text{yr}^{-1}$ ).

and the higher-latitude moisture sink, lies between 35° and 45°S. Figure 11 shows an annual cycle of this point between 30° and 45°S in the ECMWF analyses. It appears that the zero point lies farther north during the Southern Hemisphere winter. This phenomenon has been noted previously by Howarth (1986). Features in this plot are shared by the other analyses, although the magnitudes found in the ABM analyses are less.

Interestingly, the locations of the maximum net precipitation value computed from the ECMWF and NMC analyses are slightly south of those found in the other studies. At full resolution (2.5° latitude bands), the ECMWF and NMC convergence maximum is near 64°S; the other studies show the maximum to be between 50° and 60°S. The zonally averaged convergence for the ABM is a much flatter curve than the other analyses between 50° and 70°S. It is inferred that the latitude of maximum convergence is strongly influenced by the Antarctic topography. The vast escarpment along the perimeter of East Antarctica effectively blocks the southward movement of cyclones (Mechoso 1980). It is unlikely that surface-based studies would be able to sufficiently resolve this effect given the scarcity of stations. Although displaced northward, studies

by Sellers (1965), Starr et al. (1969), and Baumgartner and Reichel (1975) are in approximate agreement with the ECMWF and NMC analyses on the magnitude of the maximum. In general, the ECMWF and NMC analyses demonstrate close agreement for the Southern Ocean. Values obtained in this study for the ABM analyses are close to those obtained by Howarth (1983) and Howarth and Rayner (1986), which also employed the ABM analyses. Both are low in comparison to other studies over the Southern Ocean. For the latitude band 50°–60°S, ABM values obtained by Howarth and this study are 169 and 181  $\text{kg m}^{-2} \text{yr}^{-1}$ , respectively. The seven other analyses are an average of 305  $\text{kg m}^{-2} \text{yr}^{-1}$  greater.

In Fig. 12, zonally averaged precipitable water values are shown for 8-yr analyses averages and the rawinsonde-based values obtained from Peixoto and Oort (1983). Agreement for the Southern Hemisphere is reassuringly close. Consistent with previous results, the ECMWF is slightly larger than the other analyses for high southern latitudes, with a maximum disagreement at approximately 60°S. In contrast, NMC and ABM analyses are slightly deficient in relation to the Peixoto and Oort values for latitudes less than approximately

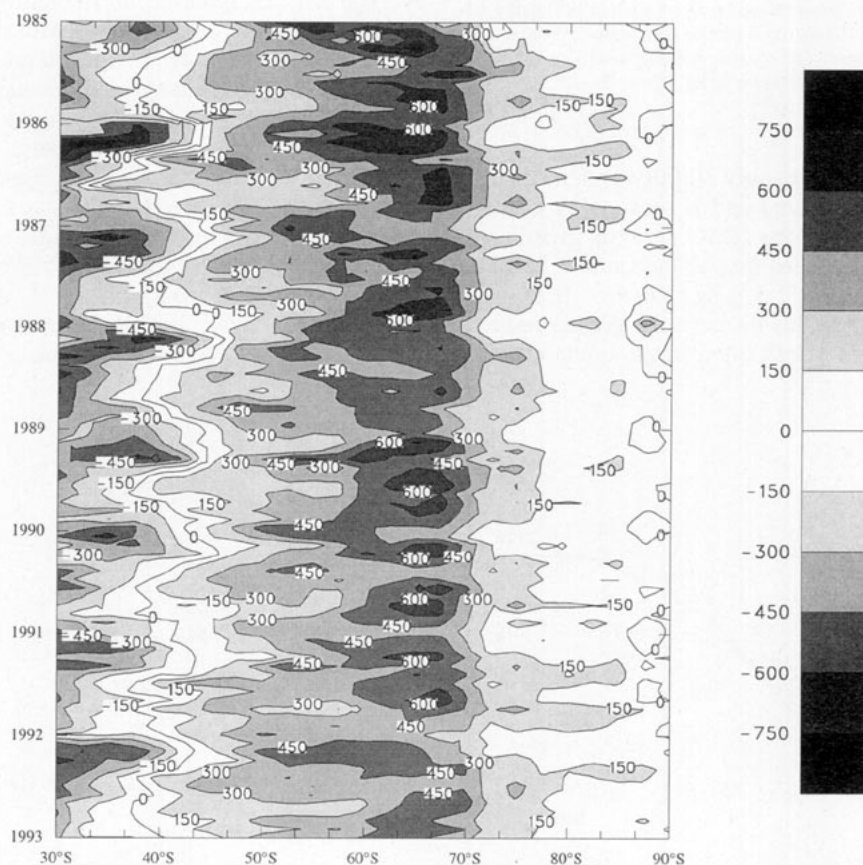


FIG. 11. Hovmöller diagram of ECMWF zonally averaged moisture convergence ( $\text{kg m}^{-2} \text{yr}^{-1}$ ) plotted as time versus latitude.

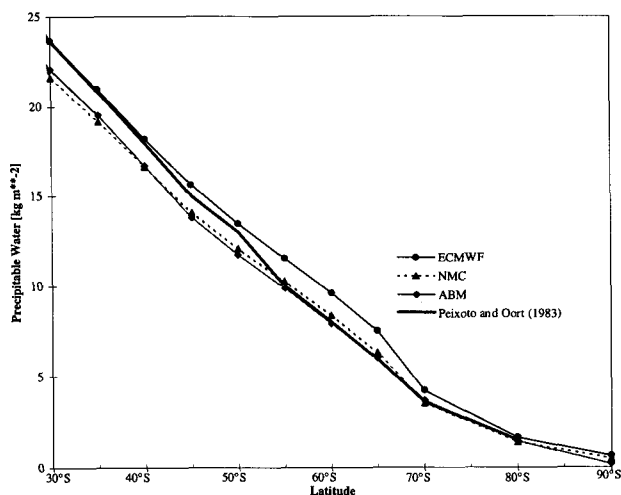


FIG. 12. Comparison of zonally averaged precipitable water ( $\text{kg m}^{-2}$ ) averaged over the 8-yr period for the three numerical analyses to radiosonde analysis by Peixoto and Oort (1983).

50°S. These differences are larger than the interannual variability seen in the analyses during the 8-yr time period but are nevertheless small.

In Fig. 13, zonally averaged, vertically integrated meridional transports for (a) total, (b) mean, and (c) eddy components are shown in comparison to available studies. In Fig. 14, zonally averaged, vertically integrated total zonal transports are shown in comparison to available studies. From the two figures it is clear that the ECMWF and NMC analyses transport values are systematically larger than those observed by Peixoto and Oort (1983). This is consistent with results obtained by Bromwich (1990). This discrepancy appears to occur equally for the mean and eddy transports. Particularly disturbing is the Fig. 13b depiction of the ABM mean transport. The differences at low and mid-latitudes in comparison to the ECMWF and NMC analyses arise from the Pacific sector, South America, and the central Indian Ocean. The pattern of the eddy moisture transports in the ABM analyses is consistent with that described by van Loon (1980). Eddy transports are markedly stronger over station locations than elsewhere, creating a cellular pattern. Thus, over the data-sparse Southern Ocean, the ABM analyses continue to substantially underestimate the eddy fluxes (e.g., Fig. 13c), as well as the convergence (Fig. 10).

### 5. Convergence for Antarctica and vicinity

Table 3 presents annually averaged values of net precipitation for polewards of 70°S and Antarctica as computed from (6). NMC values listed in Table 3 are somewhat in disagreement with those given by Yamazaki (1992). A 5-yr net precipitation average of  $162 \text{ mm yr}^{-1}$  for poleward of 70°S is given by Yamazaki (1992) for 1986–90. First, Yamazaki zonally

smoothed the divergence field near the pole. Second, the moisture convergence values given by Yamazaki were computed from the average of the divergence values computed for 5° grid boxes (Yamazaki 1995, personal communication). This method actually computes the moisture convergence for 67.5°S instead of 70°S. The meridional moisture transport increases exponentially with latitude near 70°S, and this generally accounts for the discrepancy.

Average net precipitation values shown are smaller than those determined by glaciological methods that represent a long-time average. In Giovinetto et al. (1992), net moisture convergence for 70°S was found to be  $186 \pm 37 \text{ kg m}^{-2} \text{ yr}^{-1}$ , equivalent to the same value in millimeters per year using glaciological estimates from Giovinetto and Bentley (1985) and other data. Thus, the 8-yr averages of the analyses underestimate the net precipitation by at least 4%. Consistent with the Southern Ocean comparison, the ABM analyses underestimate the long-term value by a large margin, at least 42%. For the Antarctic continent, Bromwich (1990) has estimated the long-term value as  $151\text{--}156 \text{ mm yr}^{-1}$  from the accumulation data of Giovinetto and Bentley (1985); this value has an approximate uncertainty of  $\pm 15 \text{ mm yr}^{-1}$ . Using the 8-yr average values from Table 3, the ECMWF result is found to be nearly equal to the accumulation estimate. The NMC (ABM) result is less than the observed value by at least 15% (33%). This is also consistent with the results for the Southern Ocean. In Fig. 10, the NMC and ECMWF plots diverge in the interior of Antarctica. The NMC moisture convergence is 90% of the ECMWF value for 70°–80°S, but only 30% of the ECMWF value for 80°–90°S, indicating NMC does not fare as well in the Antarctic interior. Clearly, the ECMWF performs the best among the three analyses in comparison to glaciological estimations.

From an 8-yr study, the overall long-term trend in Antarctic precipitation cannot easily be determined due to alterations to the data assimilation systems of the analyses discussed earlier. The long-term trend for moisture convergence in the NMC analyses, for example, is slightly upward from 70°S to the South Pole, and downward for Antarctica (Table 3). The trends appear to be artificial and probably results from incremental changes to the analysis scheme. The trends result from increases in the southward meridional transport and decreases in the eastward zonal transport, which is dominant along the Antarctic perimeter. These artificial trends become particularly large and obvious in the Antarctic interior. An upward trend is also somewhat apparent in the ABM analyses, which may be either real or would eventually converge with the other analyses.

Significantly, however, all three analyses indicate a marked decrease in net precipitation in 1987 and 1990. This is more clearly seen in the 12-month running means shown in Figs. 15 and 16. For the ECMWF anal-

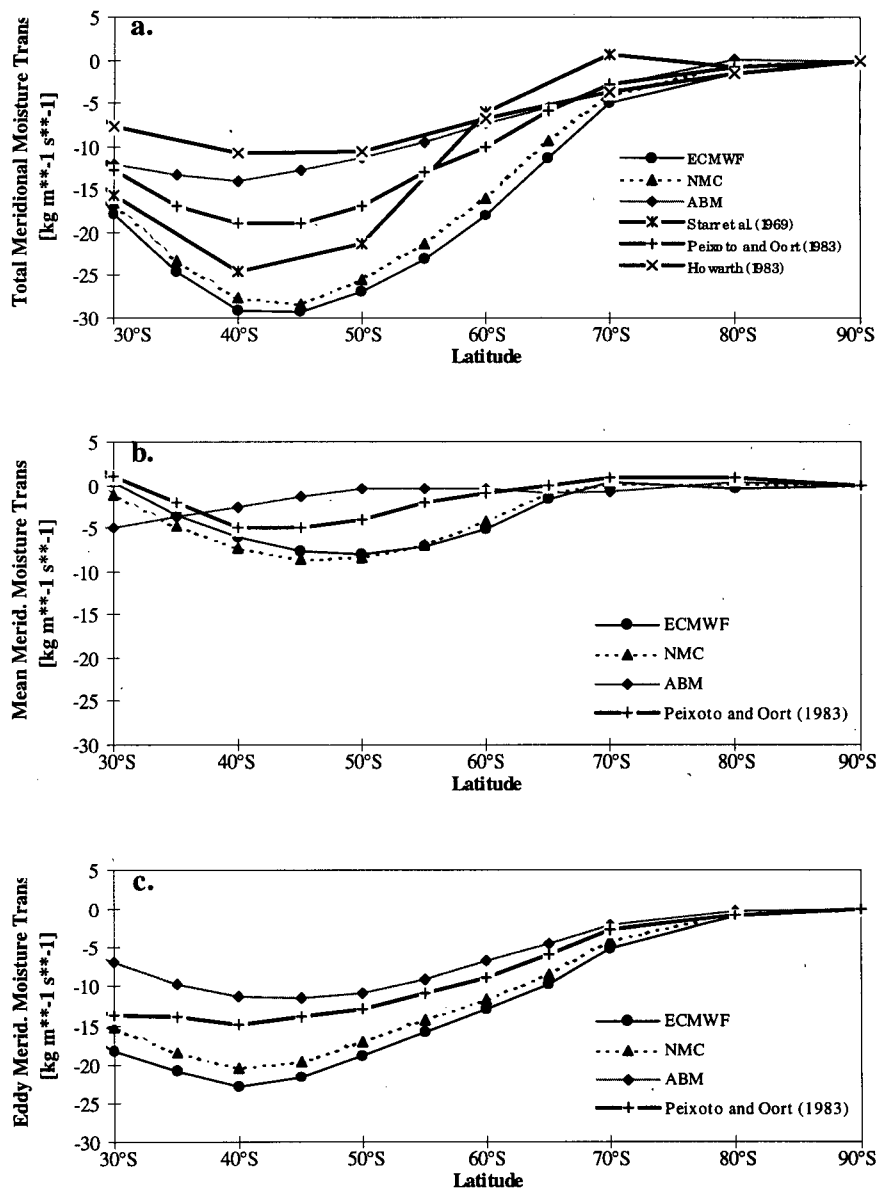


FIG. 13. Comparison of zonally averaged, vertically integrated (a) total, (b) mean, and (c) eddy meridional moisture transport ( $\text{kg m}^{-1} \text{s}^{-1}$ ), averaged over the 8-yr period, for the three numerical analyses in comparison to previous studies.

ysis, the 12-month mean beginning January 1987 is about 25% lower than the mean beginning March 1988 for moisture convergence from 70°S to the South Pole. Similar results are shown for the other two analyses.

Interestingly, changes to the numerical analyses data assimilation system are also evident here. In Fig. 15, an abrupt change occurs in the trend obtained from the ECMWF analyses for running means occurring after the May 1985 changes to the physical parameterizations and spectral resolution mentioned earlier. It is also evident from Fig. 15 that the NMC trend appears to coincide more closely with that of the ECMWF after

May 1986, when changes to the NMC analyses scheme were implemented.

In Fig. 17, (a) ECMWF and (b) NMC meridional moisture transport 12-month running means are shown for each longitude at 70°S. Clearly, the bulk of the poleward moisture transport occurs in the South Pacific sector (180°–70°W). This is consistent with results obtained by Lettau (1969). Moisture fluxes in this region can be as large as  $30 \text{ kg m}^{-1} \text{s}^{-1}$  and are predominantly from the eddy component. Outside of this sector the poleward transport is rarely above  $10 \text{ kg m}^{-1} \text{s}^{-1}$  and is usually less than  $5 \text{ kg m}^{-1} \text{s}^{-1}$ . It is also easily seen

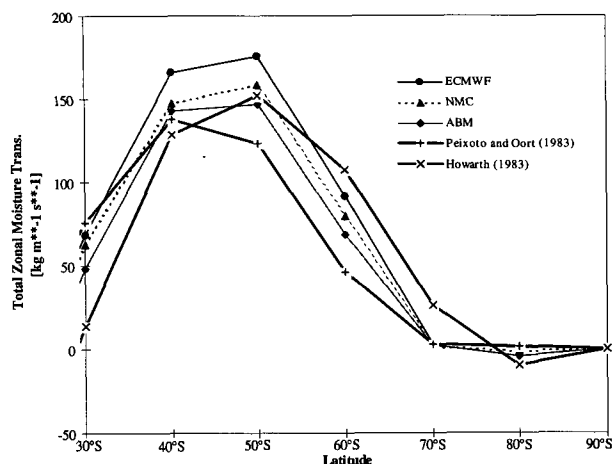


FIG. 14. Comparison of zonally averaged, vertically integrated total zonal moisture transport ( $\text{kg m}^{-1} \text{s}^{-1}$ ), averaged over the 8-yr period, for the three numerical analyses to previous studies.

that the largest interannual variability in the moisture transport occurs in this sector; very little interannual variability exists elsewhere. In Fig. 18, zonal moisture transports for the ECMWF and NMC are similarly shown. Again, the overwhelming majority of the interannual variability occurs in the South Pacific sector. In the case of the zonal transports, the variability is dramatic: maxima occur during 12-month periods beginning in early 1986 and 1991.

The primary mechanism associated with the transport of moisture into Antarctica appears to be the Amundsen Sea low, a climatological feature associated with southward-propagating storms. In Bromwich (1988), it was shown that meridional moisture fluxes observed at stations along the East Antarctic coast were consistent with nearby quasi-stationary cyclones. A similar situation occurs in West Antarctica. Figure 19 shows the interannual migration of the Amundsen Sea low. During periods of larger moisture convergence, the low occupies a position farther to the west; the moisture flux is then directed into West Antarctica. In relatively dry periods, such as in 1987, the low occupies a position farther to the east. The moisture flux is then directed toward the Antarctic Peninsula. It can be seen that the oscillations in the moisture transports observed in Figs. 17 and 18 reflect the positioning of the low as it passes through 70°S. To a large degree, the total moisture transport is in good agreement with the location of the low. The largest poleward transport is east of the cyclone center.

Because of the scarcity of data in the South Pacific sector, a degree of uncertainty exists in the ability of the analyses to properly diagnose the location of the low, and hence the interannual variability. Restated, the analyses must be able to reproduce the frequency and/or intensity of cyclonic activity in Amundsen Sea in order to determine the long-term variability of Antarctic

precipitation. In Arpe and Cattle (1993), it was noted that Antarctic monthly precipitation rates result from a small handful of synoptic events that may be handled differently depending on the analysis scheme used. This aside, it should be noted that the West Antarctic sector is not devoid of observational data. Satellite data obtained through TOVS has been incorporated into the NMC analysis throughout the 8-yr period and into the ECMWF analysis since early 1985 (Trenberth and Olson 1988c; Trenberth 1992). Additionally, several ground stations were available to the analyses during the period, notably Russkaya at 137°W (closed in March 1990) and a large number of observing stations on the peninsula.

The monthly cycle of convergence is shown for the three analyses in Figs. 20 and 21 for 70°–90°S and Antarctica, respectively. As was noted by Yamazaki (1992), a distinct semiannual oscillation is found, particularly for 70°–90°S. The analyses indicate moisture convergence maxima occur in May and September/October. This phenomenon has been observed in station precipitation data (Bromwich 1988; Eicken et al. 1994, see their Fig. 9), especially in the Weddell Sea area. Not shown here, an examination of the annual variability in the Amundsen Sea low shows a similar pattern to that seen on the interannual timescale, with the low moving farther east during months of smaller moisture convergence values.

## 6. Summary and conclusions

An examination of moisture fluxes in high southern latitudes has been performed using the numerical analyses produced by operational forecast centers. At Macquarie Island, reasonable agreement is found for the ECMWF and NMC moisture fluxes with observations, while the ABM analysis is deficient by a noticeable amount. All three analyses reproduce the interannual variability in the moisture fluxes seen at Macquarie Island. Good agreement is also noted in the estimation of precipitable water for the NMC and ABM analyses,

TABLE 3. Comparison of annual net moisture convergence for south of 70°S and Antarctica, from the three numerical analyses.

Year	70°–90°S			Antarctica		
	ECMWF	NMC	ABM	ECMWF	NMC	ABM
1985	136	121	66	141	136	80
1986	150	123	67	174	124	87
1987	118	110	69	141	94	85
1988	141	148	82	148	98	84
1989	144	155	93	156	110	105
1990	127	118	82	142	77	82
1991	151	144	100	161	103	98
1992	154	155	92	190	122	93
Average	140	134	81	157	108	89
Std. error	4	6	5	6	7	3



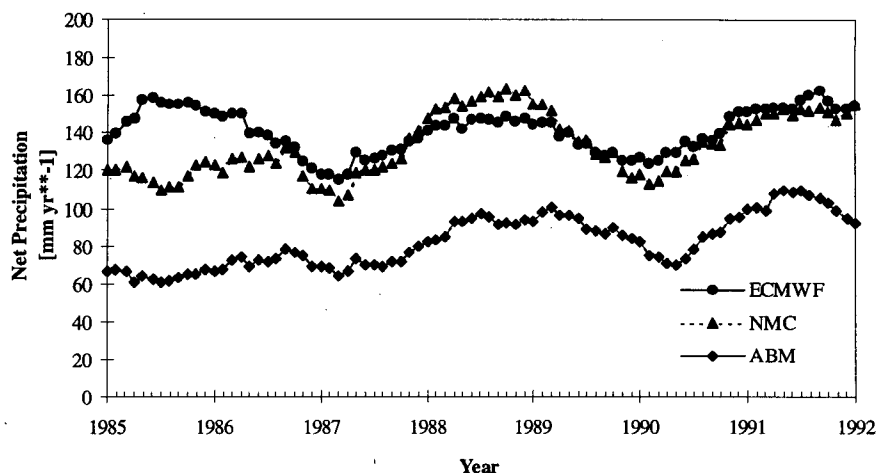


FIG. 15. Twelve-month running mean annual net precipitation ( $\text{mm yr}^{-1}$ ) for poleward of  $70^{\circ}\text{S}$ .

however, a systematic overestimation of precipitable water is found in the ECMWF analyses for this station. For Antarctica the agreement between rawinsonde data and analyses is not as compelling, although there is reasonable evidence to suggest that a great deal of the rawinsonde observations is being incorporated into the analyses. Particularly encouraging is the ability of the ECMWF to reproduce low-level inflow and outflow patterns observed along the East Antarctic coast. A comparison of moisture convergence for East Antarctic boundaries defined by Bromwich (1988) indicates good agreement between the ECMWF analyses and observation. Agreement is within  $5 \text{ mm yr}^{-1}$ . The NMC analyses greatly underestimate the East Antarctic moisture convergence due to inaccuracy at the 850-hPa level. An overall deterioration in the ability of the analyses occurs for the easternmost stations.

The comparison of numerical analyses to rawinsonde data again indicates variability in analyses skill

depending on the station. Generally, the ECMWF analysis appears to be superior at reproducing the rawinsonde values at each level; the comparison of the East Antarctic moisture convergence demonstrates a high degree of reliability with this analysis. Despite the rather large overestimation of precipitable water by the ECMWF, it is apparent that the majority of the transport error at each level occurs in the wind field rather than the specific humidity. This is not surprising given the monotonic nature of the specific humidity profile and the complexity of the katabatic flow.

A comparison of moisture fluxes in the Southern Ocean is made to previous atmospheric hydrologic studies employing a variety of methods and observing periods. There is broad disagreement among the various studies in the magnitude of convergence (precipitation minus evaporation); however, there was agreement on the location of the midhemispheric zero point. The ABM analysis was low in comparison to the other

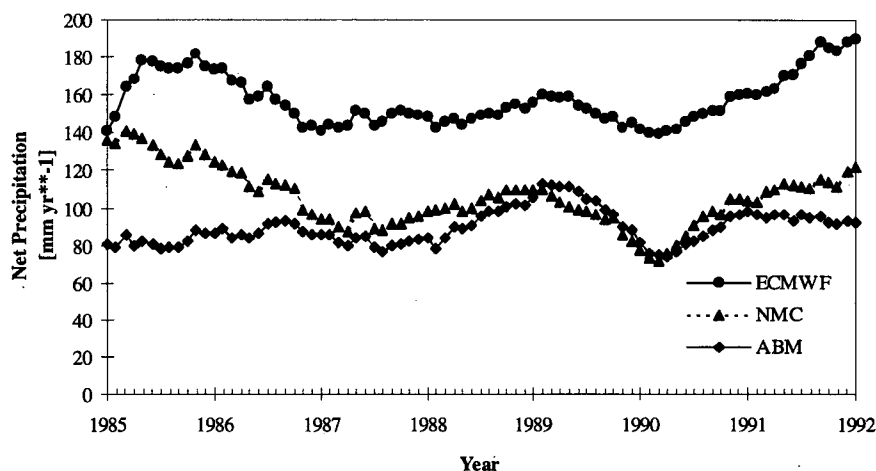


FIG. 16. Twelve-month running mean annual net precipitation ( $\text{mm yr}^{-1}$ ) for Antarctica.

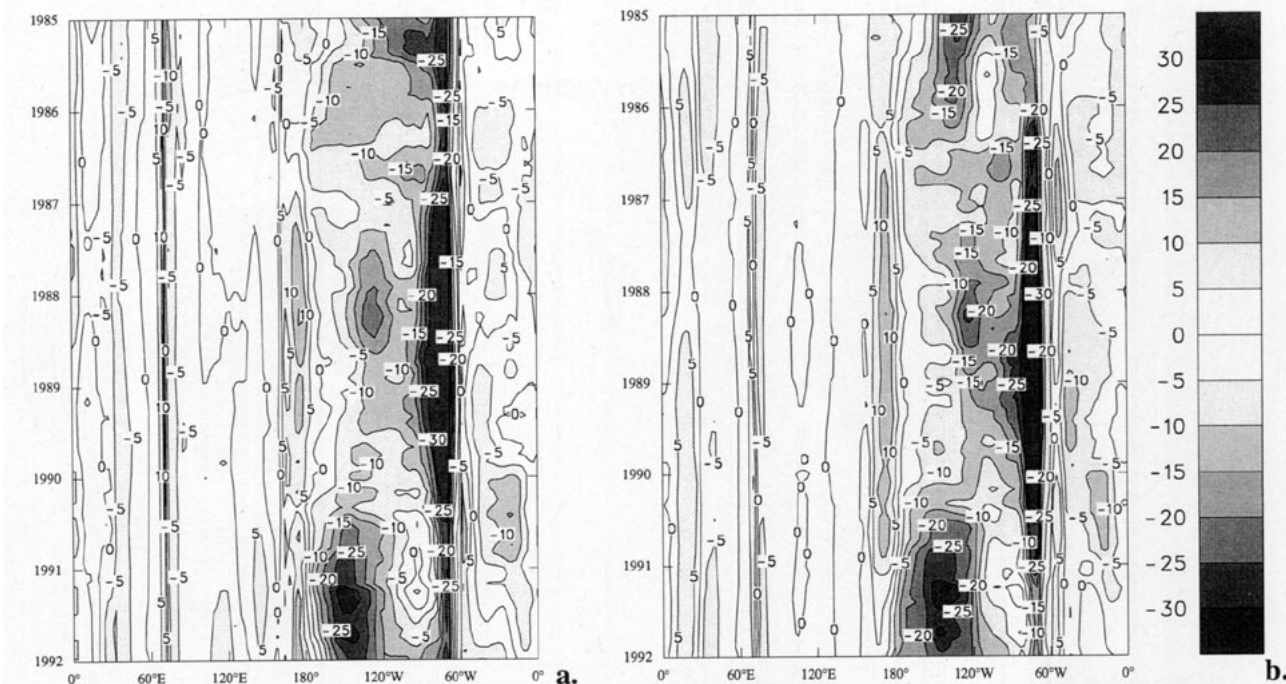


FIG. 17. Hovmöller diagram of vertically-integrated meridional moisture transport ( $\text{kg m}^{-1} \text{s}^{-1}$ ) at 70°S, plotted versus longitude, for (a) ECMWF and (b) NMC. Dates indicate the beginning of each 12-month running mean.

studies and analyses. The magnitudes for Peixoto and Oort (1983) were found to be smaller than those computed for the NMC and ECMWF analyses, which is

consistent with results found by Bromwich (1990). The magnitude of the maximum value for convergence in the NMC and ECMWF analyses agrees with several

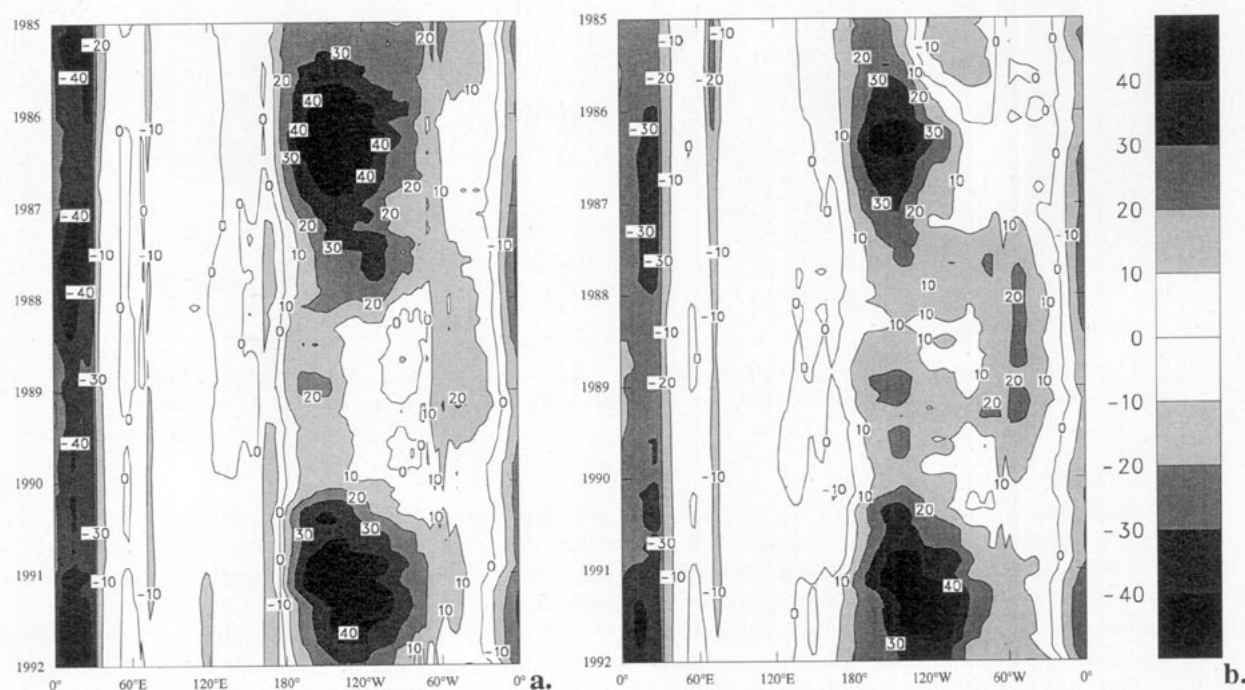


FIG. 18. Hovmöller diagram of vertically integrated zonal moisture transport ( $\text{kg m}^{-1} \text{s}^{-1}$ ) at 70°S, plotted versus longitude, for (a) ECMWF and (b) NMC. Dates indicate the beginning of each 12-month running mean.

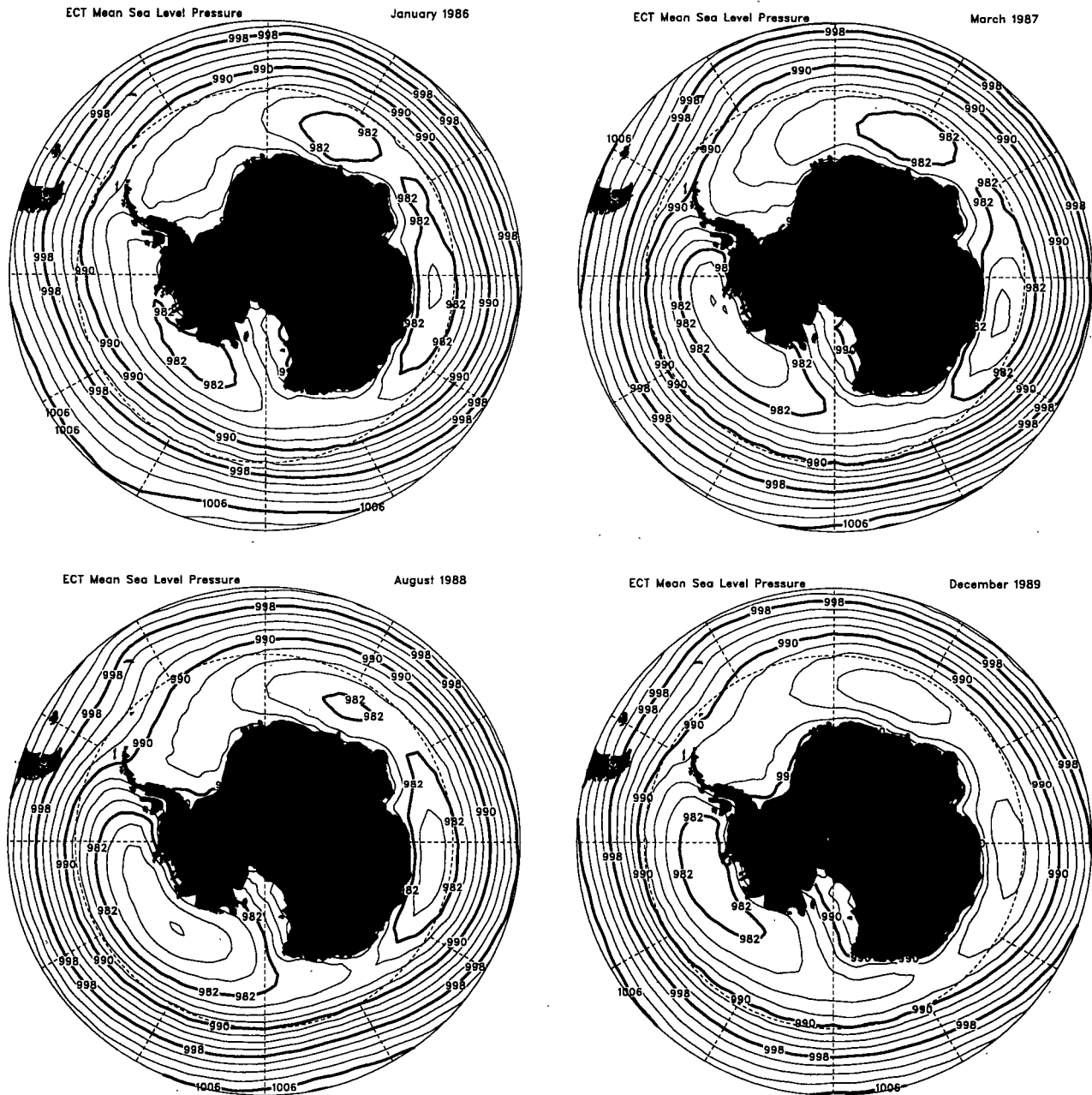


FIG. 19. ECMWF sea level pressure fields for 12-month means beginning (a) January 1986, (b) March 1987, (c) August 1988, and (d) December 1989, contoured every 2 hPa. Bold contours are shown for every 8 hPa.

surface-based observations, however, the location of the maximum is farther south in the analyses. It is inferred that this results from the incorporation of Antarctic topography by the analyses. Comparisons were also performed between meridional and zonal total, mean, and eddy moisture transports with available studies. There was a great deal of agreement between the NMC and ECMWF analyses over the Southern Ocean, especially after 1986, however, the two analy-

ses disagree over the interior of Antarctica. Particularly disturbing are the differences in the ABM mean meridional transport with the other analyses and previous studies.

Estimations of annual and monthly net precipitation values for Antarctica by the three analyses are found to be less than obtained from long-term surface methods. By far the largest contribution is from the South Pacific sector ( $180^{\circ}$ – $70^{\circ}$ W). A clearly discernible in-

terannual variation occurs in this sector, in response to migrations of the Amundsen Sea low. Net precipitation derived from the analyses varies by approximately 25% over interannual time periods. Significant interannual variability does not appear in any other sector. Semi-annual maxima in net precipitation are found in the analyses.

The results of this examination point to several areas that require further study. As indicated by the analyses, the importance of the Amundsen Sea low to the net precipitation rate for Antarctica is significant; the available data on the frequency and intensity of cyclonic activity in this area is limited. As has been indicated, however, the Pacific sector is not devoid of data. Brown and Zeng (1994) evaluated ECMWF and NMC oceanic surface pressure fields using *ERS-1* scatterometer winds in a planetary boundary layer model. Most storms in the Southern Hemisphere were picked up by both analyses, with some exceptions. Improvements in the detection of Southern Ocean cyclonic activity would enhance the accuracy of the analyses. The results presented here nevertheless offer a substantially more positive outlook on the prospects of determining precipitation trends in Antarctica through atmospheric methods than was previously found (Bromwich 1990). One means of addressing analyses deficiencies currently underway is the First Regional Observing Study of the Troposphere (FROST; Bromwich and Smith 1993). The primary purpose of FROST is to verify Antarctic analyses and model forecasts and to discover if additional data inputs and modifications to numerical analyses and models can improve forecasts. Results obtained through FROST should greatly improve the skill of the analyses, particularly in data-sparse areas where the skill has not been accurately addressed. The introduction of consistent analysis procedures (e.g., Bengtsson and Shukla 1988; Kalnay and Jenne 1991) should further improve the reliability of this method.

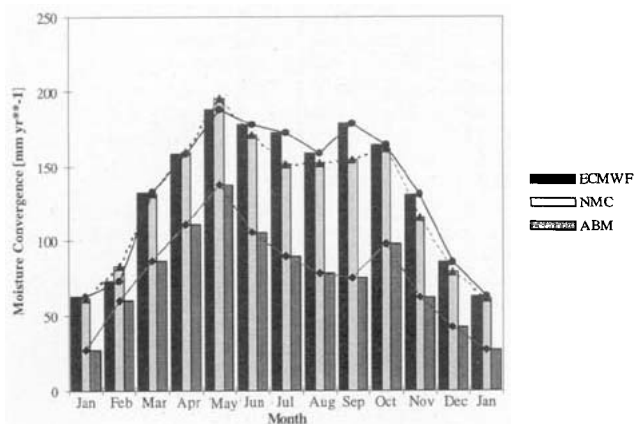


FIG. 20. Monthly moisture convergence ( $\text{mm yr}^{-1}$ ) for polewards of  $70^\circ\text{S}$  averaged over eight years.

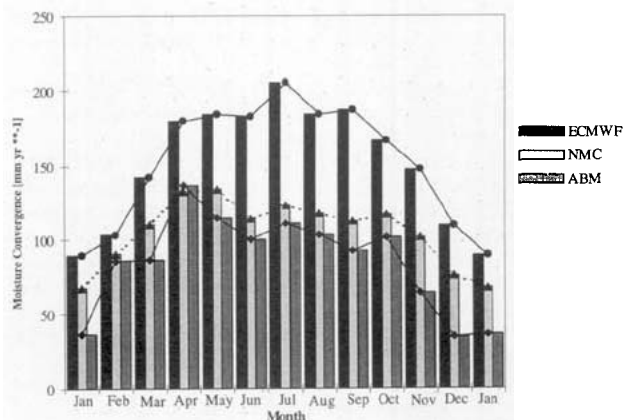


FIG. 21. Monthly moisture convergence ( $\text{mm yr}^{-1}$ ) for Antarctica averaged over eight years.

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